ON THE DISTRIBUTION OF RADIOGENIC HEAT PRODUCING ELEMENTS AND THE DERIVED GEOTHERMAL MODEL OF THE CONTINENTAL CRUST

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To have a relevant model of the crust, which would allow to extrapolate the near surface geothermal data to depth and to evaluate the crustal temperatures, the knowledge of the distribution of heat producing radioactive elements is essential. Most of current heat production models are derived from the presumed petrological crustal models completed with laboratory measurements of radioactive content of rock samples representing a suite of characteristic crustal types. The experimental relationship between seismic velocity (v_p) and heat production (A), formulated by Rybach and Buntebarth (1984), provided a useful independent method to evaluate crustal heat sources. After considering for the pressure and temperature dependences of the seismic velocity and after taking into account the dependence of the heat production on the geological age (see also Čermák and Bodri, 1986; Čermák, 1988) the v_p-A conversion allows to characterize the individual crustal layers in terms of their heat production.

Crustal radioactivity may have been considerably affected by various secondary processes, such as igneous, metamorphic and tectonic activity, subsurface fluid movements, etc. It is clear that a simple functional expression A(z) can hardly be applicable for the whole continental crust without taking into account local crustal features. Nevertheless, a certain general relationship is often needed in order to compare the individual tectonic provinces and to assess the heat flow contribution (Moho heat flow) from depth. A number of heat production models have been proposed and discussed in literature (Roy et al., 1968; Lachenbruch 1968). Generally these models were derived from the observed heat flow--near surface heat production data. The problem, however, arises, whether the near surface phenomena can be extrapolated to the whole crust, and if e.g. simple exponential heat production distribution $A(z)=A_0\exp(-z/D)$ is suitable for deep temperature calculations. Exponential decrease of heat production with depth, identifying the parameter D as a general geochemical property, reasonably well describes the upward concentration of radioactive elements, being the consequence of partial melting during the crustal formation.

The radiogenic heat production is a composite contribution of U, Th and K and it is natural to expect that the distribution of each element is governed by its own depth dependence. This would result in a certain depth deviation of the D-parameter from a value found from the near surface observations, namely in the gradual increase of the D-value with depth. In the lower crust the element with the highest D-value has to take over and controls the heat production. The relative enrichment of the upper parts of the crust by radioelements by secondary processes during the crustal evolution was proposed by several authors. Especially Uranium is vulnerable to the effect of deep penetrating meteoric water and U can thus be leached away from deeper rocks and be relatively more abundant in the uppermost crustal sections. Costain (1978) threw doubts on a universal validity of simple exponential distribution A(z) characterized by a single value of D within the whole crust and suggested that the zone of microcrack porosity and the depth of emplacement of igneous rocks might play an important role in the observed linearity between surface heat flow and near surface heat production.

This paper is a thorough analysis of v_p-A converted data from a numerous $v_p(z)$ profiles from various tectonic units in Europe and North America with a few more localities in India, Africa and Australia. In addition to previous papers, which employed similar data from Central and Eastern Europe in order to assess the crustal heat contribution and to calculate Moho heat flow (Čermák, 1988) and to speculate on the vertical distribution of heat production in the continental crust (Čermák and Rybach, 1988), this paper focussed on the application of statistical criteria to find the best fitting A(z) expression corresponding to the observed material.

The empirical relationships between seismic velocity and heat production (Rybach and Buntebarth, 1984) are based on laboratory measurements and correspond to certain fixed laboratory conditions, namely to 20°C and 100 MPa. As seismic velocity is temperature and pressure dependent, before the v_p-A conversion can be applied on observed seismic velocities, the T, P effects on v_p must be assessed. For detailed studies of the vertical distribution of heat sources, each individual $v_p(z)$ profile treated in this work was therefore converted into A(z) profile separately taking into account the specific local conditions. Rather than to use correction factor $f=v_p(20,100)/v_p(T,P)$ (proposed by Rybach and Buntebarth, 1984), more complex correction function C(z) was introduced, $f=1+C(z)/v_p$. For a standard density(pressure)-versus-depth model and for a temperature-versus-depth model (depending on the surface geothermal activity), the C(z) can be expressed directly as a function of depth, including the pressure and temperature derivatives of the seismic velocity (for details see Čermák, Bodri and Rybach, in preparation).

Due to extreme complexity of the uppermost crust and to certain problems of applying the conversion v_p-A technique properly at pressures up to 200-300 MPa, the upper-ten-kilometers layer was not considered. The following consideration therefore refers only to the bulk of the crust below 10 km depth (Čermák, 1988).

As a result of the v_p-A conversion, a number of corresponding A(z) profiles were obtained, which were then analysed and compared with a series of simple models : single, double and triple step models, linear model and several exponential models. As no special A(z) function had been preferred and basically only two requirements were postulated : (i) A(z) function must be decreasing with depth, and (ii) dA/dz negative, its absolute value also be decreasing with depth. This means, that e.g. linear model $A(z)=A_0(1-z/D)$ (even when statistically gave reasonably good approximation) was disqualified. It was found that the exponential functions correspond best to the studied A(z) profiles, indicating however, a certain systematic depth deviation, which could be expained by a depth depending logarithmic decrement D(z) (Čermák and Rybach, 1988).

The following exponential-type distributions were studied :

(a) $A(z)=A_0\exp(-z/D)$ with D constant in the whole crustal section below 10 km;
(b) ibid, with D being different in specific crustal layers, namely 10-20, 20-30, 30-40 km;
(c) $A(z)=A_0\exp[-z/(D+\alpha z)]$, depth dependent D-parameter;
(d) $A(z)=A_1\exp(-z/D_1) + A_2\exp(-z/D_2)$, which corresponds to two-component heat production, and
(e) $A(z)=A_0[(1+\alpha z)\exp(-z/D_1) + \exp(-z/D_2)]$, also a two-componet heat production with a depth dependent ratio of the individual contributions.

Both latter distributions were applied also on converted heat production data after the contribution of potassium (generally characterized by large D_K and practically constant with depth) was removed. However, the solutions of both these distributions, quite complex, suffered from poor stability (4 parameters to be estimated).

The present paper focuseed therefore on two former distributions. For them the non-linear least squares problem was solved with the help of the conjugate gradient method and the goodness of fit was tested by Fischer criterion, only results at the 95 % confidence level were accepted.

More than 150 individual $v_p(z)$ profiles were investigated, grouped into several categories according to their tectonic age/geological history and surface heat flow. As there is a generally negative correlation between surface heat flow and crustal thickness (Čermák, 1982), the above subgrouping relates also to the mean Moho depth, being the further parameter to be incorporated into the study. Some of the characteristic results are compiled and shown in Table 1, defining the mean (calculated) heat production at depth 10 km and the mean D-value for selected tectonic units (the results of the calculation (a)) and the characteristic D-values corresponding to intervals 10-20, 20-30 and 30-40 km (the results of the calculation (b)).

TABLE 1. Calculated mean heat production at depth of 10 km and the mean value of the logarithmic decrement D characterizing the whole crust together with values of D-parameter corresponding to the specific depth intervals of 10-20, 20-30, and 30-40 km.

Tectonic unit	n	A_0 $\mu W.m^{-3}$	D km	D_{10-20} km	D_{20-30} km	D_{30-40} km
North America						
Canadian shield	4	0.77	11	17	11	5
Canadian Rockies	1	0.76	12	14	11	9
Canadian Cordillera	7	1.83	15	38	8	4
Central and Eastern US	1	0.68	14	29	13	5
Northern Rockies	6	1.96	12	31	13	9
Basin and Range	8	2.17	11	18	6	-
Colorado Plateau	8	2.11	12	15	8	-
Europe						
Baltic shield	5	0.58	19	13	22	(26)
Ukrainian shield	7	0.47	19	19	18	(21)
East European Platform	9	0.52	18	34	12	14
Bohemian Massif	4	2.07	12	14	9	(23)
Northern Great Britain	5	1.72	13	19	9	4
French Massif Central	8	1.73	14	29	6	-
Pannonian Basin	2	1.74	8	9	(24)	-
Eastern Mediterranean	1	(4.79)	5	5	4	-
Africa						
East African Rift	5	2.25	11	13	8	6
Asia						
Indian shield	1	0.35	19	21	15	13
Australia						
Western shield	7	0.58	10	29	15	8
South-East region	6	2.12	11	16	13	8

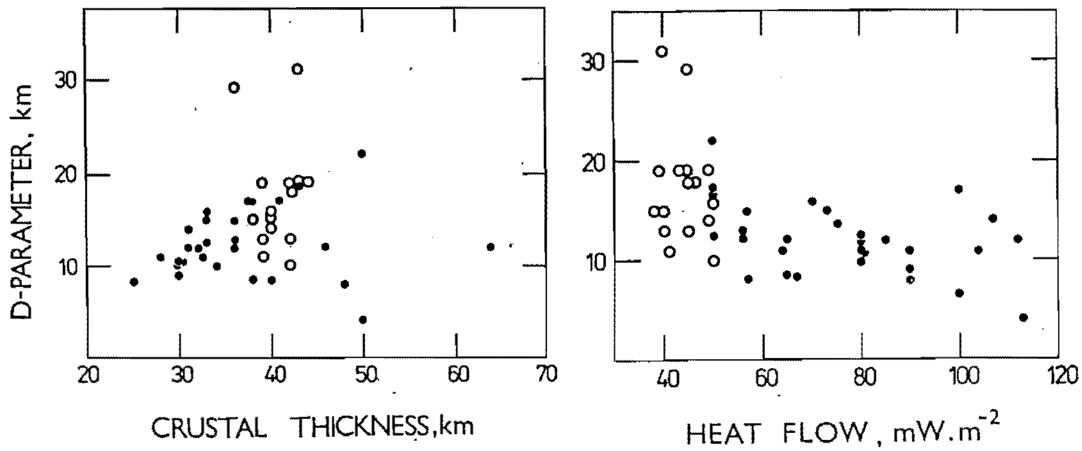
Among the most important pieces of knowledge deduced from the performed analysis one has to emphasize:

(1) The mean value of the D-parameter of the simple exponential distribution A(z) generally decreases with the age, D-parameter amounts 15-20 km in the Precambrian units compared with about 10 km in the Phanerozoic realm. In the latter Phanerozoic group the mean D-parameter decreasing with increasing surface heat flow. D-parameter is approximately equal to half of the crustal thickness in ancient cratons and platforms, and only about 1/3 in younger units. This finding suggests more pronounced differentiation of the radioactive elements (steeper heat production distribution) in younger terrains.

(2) The value of A_0 is practically constant in Precambrian units (0.5 - 0.7 $\mu W.m^{-3}$) and considerably smaller than in Phanerozoic units (1.5 to 2.0 $\mu W.m^{-3}$).

(3) If characteristic values of the D-parameter were calculated for the individual crustal layers, D-parameter generally decreases with depth. This decrease is typical for all studied regions, being less pronounced in ancient shields than in platforms, being quite distinct in younger terrains. The value of the D-parameter is of 20-35 km just below 10 km depth, abruptly decreasing to about one half below 20 km and remaining practically constant in deeper sections.

(4) Positive correlation exists between D-value and the Moho depth (coefficient of correlation better than 0.9), see Fig.1. Negative correlation exists between D-value and surface heat flow (coefficient of correlation of about -0.85), see Fig.2.



Figures 1 and 2. Correlation between calculated D-parameter and Moho depth (left) and D-parameter and surface heat flow (right). Open circles correspond to Precambrian units (shields and platforms), solid dots correspond to Phanerozoic terrains

Conclusions :

The conversion of compressional seismic velocity into heat production yields a general decrease of heat production with depth. This depth dependence needs not to follow exactly a simple exponential law. Summarizing the idea of the role of underground water circulation in the redistribution of the radioactive elements (Costain, 1978; Gosnold and Swanberg, 1980) together with our finding of the principal disagreement between the extrapolated (geochemical) D-parameter (increasing with depth) and converted heat sources distribution (decreasing D with depth) (Čermák and Rybach, 1988), the following model was proposed (Fig.3).

The "original" distribution of heat sources was preserved in the lower crust and can be hardly identified from the near surface observations. If approximated by a general exponential curve, the D-parameter decreases with depth, i.e. deeper in the crust the heat production decreases more rapidly with depth than in the intermediate parts of the crust. This decrease is more pronounced within younger or high heat flow provinces than in old shields and platforms.

At depths below 25-30 km the contribution to heat flow is very small and there is no considerable difference between heat generation in the lowest crust and the uppermost mantle. Near the surface, at depths less than the D-parameter (i.e. in the upper 7-14 km), the subsequent processes (magmatism, metamorphism, hydrogeological alternation, etc.) caused a certain redistribution of radiogenic elements. Groundwater circulation plays a decisive role in producing upward migration and enrichment of uranium. Although there is probably no distinct transition zone separating the uppermost crust (defined as a region of meteoric water penetration, Čermák and Rybach, 1988) from the underlaying unaffected crustal layers, the existence of some inversion zone at depth close to 10 km cannot be precluded. This would correspond to the inflection in the heat production-depth curve at the lowest depths of interaction between plutons and groundwater (Gosnold and Swanberg, 1980). The heat production within the upper can be evaluated from the combined heat flow-heat generation studies where the D-parameter corresponds to the slope of the linear relationship (Roy et al., 1968). The uppermost crustal rocks are enriched in radioelements while the rocks at the base of this layer are depleated with respect of the original distribution.

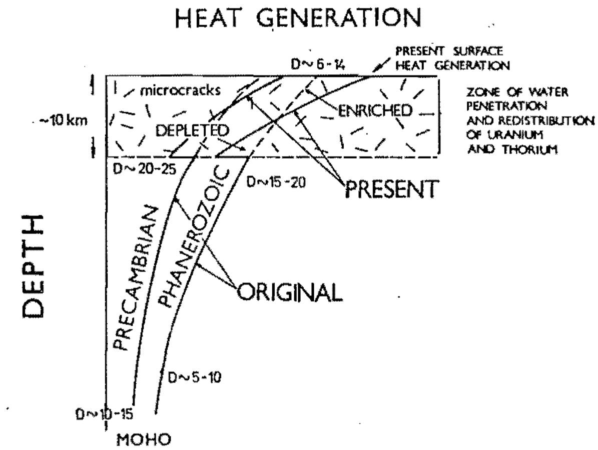


Fig.3. Model proposed for radioelement redistribution in the uppermost crust, also indicating schematically the variation of D-value (in km) with depth.

References :

Čermák, V., 1982. Crustal temperature and mantle heat flow in Europe. Tectonophysics, **83**: 123-142.
Čermák, V., 1988. Crustal heat production and mantle heat flow in Central and eastern Europe. Tectonophysics (in press).
Čermák, V., and Bodri, L., 1986. Two-dimensional temperature modelling along five East-European geotraverses. J.Geodynamics, **5**, 133-163.
Čermák, V., and Rybach, L., 1988. Vertical distribution of heat production in the continental crust. Tectonophysics (in press).
Costain, J.K., 1978. A new model for the linear relationship between heat flow and heat generation. EOS, Trans.AGU., **59**. 392.
Gosnold, W.D., and Swanberg, C.A., 1980. A new model for the distribution of crustal heat sources. EOS, Trans.AGU., **61**: 387.
Lachenbruch, A.H., 1968. Preliminary geothermal model of the Sierra Nevada. J.Geophys.Res., **73**: 6977-6989.
Roy, R.F., Blackwell, D.D., and Birch, F., 1968. Heat generation of plutonic rocks and continental heat flow provinces. Earth Planet.Sci.Lett., **5**: 1-12.
Rybach, L., and Buntebarth, G., 1984. The variation of heat generation, density and seismic velocity with rock type in the contunental lithosphere. Tectonophysics, **103**: 335-344.